

AR Scorpii is a new white dwarf in the ejector state

N.G. Beskrovnaya¹ and N.R. Ikhsanov^{1,2,3}

¹*Pulkovo Observatory, Saint-Petersburg, Russia; beskrovnaya@yahoo.com*

²*SAO RAS, Nizhni Arkhyz, Karachai Cherkessia, Russia*

³*Saint-Petersburg State University, St. Petersburg, Russia*

Abstract. Marsh et al. (2016) have recently reported the discovery of a radio-pulsing white dwarf in the cataclysmic variable AR Sco. The period of pulsations which are also seen in the optical and UV is about 117 seconds. High intensity of pulsing radiation and non-thermal character of its spectrum leave little room for doubt that the white dwarf in AR Sco operates as a spin-powered pulsar and, therefore, is in the ejector state. We show that this system is very much resembling a well-known object AE Aqr. In both systems the compact components are spin-powered and have relatively strong surface magnetic field of order of 100-500 MG. They originated due to accretion spin-up in the previous epoch during which the magnetic field of the white dwarf had substantially evolved being initially buried by the accreted matter and recovered to its initial value after the spin-up phase had ended.

1. Introduction

Information about unique properties of AR Sco has been published quite recently (Marsh et al. 2016) and immediately excited much interest. This is a close binary with the orbital period of ~ 3.56 h containing a red dwarf of spectral type M and a white dwarf spinning at the period of ~ 117 s. The most peculiar feature of this object is that the spin period of the white dwarf is increasing so rapidly that its spin-down power exceeds the bolometric luminosity of the system emitting electromagnetic radiation from radio to X-rays. Moreover, the white dwarf is a radio-pulsar as well as a pulsar in the IR, optical and UV spectral domains. The intensity of pulsed emission in the optical region exceeds the total emission of the stellar components. The spectrum of radio-emission is non-thermal and characterized by anomalously high brightness temperature. Marsh et al. (2016) have concluded that the white dwarf in AR Sco is spin-powered and in the ejector state.

In spite of all unique properties, AR Sco is not the only system containing a white dwarf in the ejector state, i.e. spending its rotation energy according to the canonical model of a radio-pulsar at a rate which exceeds the observed source luminosity. It shares this property with the white dwarf of AE Aquarii (AE Aqr) which is spinning at the period of 33 s and exhibits a period derivative of $5.64 \times 10^{-14} \text{ ss}^{-1}$ (de Jager et al. 1994). Its spin-down power under these conditions exceeds the bolometric luminosity of the system (observed in the wide range from radio to X-rays) and can be explained within the conventional spin-powered pulsar model provided the magnetic moment of

the white dwarf is $\mu \sim 10^{34} \text{ G cm}^3$, which implies the surface magnetic field of 50 – 100 MG (Ikhsanov 1998; Ikhsanov & Biermann 2006).

2. Magnetic field of the white dwarf in AR Sco

In the case of AR Sco the spin-down power can be inferred from observations as

$$L_{\text{sd}} = I\omega_s\dot{\omega}_s \simeq 9.7 \times 10^{32} \text{ erg s}^{-1} \times I_{50} P_{117}^{-3} \left(\frac{\dot{P}}{3.9 \times 10^{-13} \text{ s s}^{-1}} \right), \quad (1)$$

where I_{50} and P_{117} are the moment of inertia and the spin period of the white dwarf in units of 10^{50} g cm^2 and 117 s, respectively. On the other hand, the spin-down power of a spin-powered pulsar with the angular velocity ω and dipole magnetic moment μ can be expressed following Spitkovsky (2006) as $L_{\text{rot}} \approx (\mu^2 \omega^4 / c^3)(1 + \sin^2 \alpha)$, where α is the angle between the magnetic and rotation axes. Solving equation $L_{\text{sd}} = L_{\text{rot}}$ for μ and assuming $\alpha \sim \pi/2$ one finds a lower limit to the dipole magnetic moment of the white dwarf in AR Sco within the spin-powered white dwarf scenario as

$$\mu \sim 5.6 \times 10^{34} \text{ G cm}^3 \times I_{50}^{1/2} P_{117}^{1/2} \left(\frac{\dot{P}}{3.9 \times 10^{-13} \text{ s s}^{-1}} \right). \quad (2)$$

This implies that the magnetic field strength at the equator of the white dwarf of mass M_{wd} and radius R_{wd} is

$$B \sim 150 \text{ MG} \times k_{0.33} \left(\frac{M_{\text{wd}}}{0.8 M_{\odot}} \right)^{1/2} \left(\frac{R_{\text{wd}}}{7 \times 10^8 \text{ cm}} \right)^{-2}, \quad (3)$$

where the moment of inertia of the white dwarf $I = k^2 R_{\text{wd}}^2 M_{\text{wd}}$ and the radius of gyration $k_{0.33} = k/0.33$ is normalized following Frank et al. (2002).

3. Origin of AR Sco

3.1. Spin-up epoch

A possible formation of the ejector white dwarf in the process of binary evolution was considered in detail in a previous paper (Ikhsanov & Beskrovnaya 2012) dedicated to the overview of peculiar properties and origin of AE Aqr. The developed approach can be used here since the white dwarf in AR Sco is currently spinning down at the time-scale $t_{\text{sd}} \simeq P_s/2\dot{P} \simeq 10^7 \text{ yr}$, while its age determined by the cooling time is much longer. Indeed, the cooling time of the white dwarf with the surface temperature $T_{\text{wd}} \sim 10\,000 \text{ K}$ and mass $M_{\text{wd}} \sim (0.8 - 1.3) M_{\odot}$ is $\gtrsim 10^9 \text{ yr}$ (Schönberner et al. 2000). A natural conclusion is that fast rotation of the white dwarf is not caused by the singularity of its birth but is a consequence of peculiar binary evolution incorporating the stage of rapid spin-up of the white dwarf due to high-rate accretion onto its surface.

A white dwarf can undergo a significant accretion-driven spin-up only under condition $\dot{M}_{\text{su}} > \dot{M}_{\text{cr}}$, where $\dot{M}_{\text{cr}} \simeq 10^{-7} M_{\odot}/\text{yr}$ is a critical rate which provides a stable burning of hydrogen in the matter accreted onto its surface (see, e.g. Nomoto et al. 2007, and references therein). Otherwise, the situation would resemble the dwarf novae in which the angular momentum is effectively carried away from the white dwarf by

the expanding envelope formed in the novae outburst due to thermonuclear runaways on its surface (Livio & Pringle 1998). For $\dot{M}_{\text{su}} \sim \dot{M}_{\text{cr}}$ the duration of the spin-up stage is (Ikhsanov 1999)

$$t_{\text{su}} \geq \frac{2\pi I}{\dot{M}_{\text{su}} \sqrt{GM_{\text{wd}} R_{\text{m}}}} \left(\frac{1}{P} - \frac{1}{P_0} \right) \approx 1.2 \times 10^5 \text{ yr} \times I_{50} \dot{M}_{19}^{-1} M_{0.8}^{-1/2} R_9^{-1/2} P_{117}^{-1}, \quad (4)$$

where $P_0 \gg P$ is an initial spin period of the white dwarf. Here R_9 is its magnetospheric radius, R_{m} , at the end of the spin-up epoch expressed in 10^9 cm, $M_{0.8} = M_{\text{wd}}/0.8M_{\odot}$ and $\dot{M}_{19} = \dot{M}_{\text{su}}/10^{19} \text{ g s}^{-1}$.

3.2. Screening of magnetic field

In the process of accretion-driven spin-up the white dwarf could reach the period $P \leq 117$ s only if its magnetospheric radius at the final stage of the spin-up epoch, R_{su} , did not exceed the corotation radius, i.e. $R_{\text{su}} \leq R_{\text{cor}}$, from which we estimate the magnetic field strength of the white dwarf at the end of the spin-up stage as $B_s \leq B_0$, where

$$B_0 \approx 10 \text{ MG} \times M_{0.8}^{5/6} P_{117}^{7/6} \dot{M}_{19}^{1/2} \left(\frac{R_{\text{wd}}}{7 \times 10^8 \text{ cm}} \right)^{-3}. \quad (5)$$

This means that the magnetic field strength of the white dwarf should significantly vary in the course of AR Sco evolution. It decreased by a factor of ~ 50 during the spin-up epoch and returned to its initial value upon its completion. Such evolution of the magnetic field could result from its screening by the accreting material (Bisnovatyi-Kogan & Komberg 1974). A possibility to bury the magnetic field of accreting compact objects was investigated for both the neutron stars (Konar & Choudhuri 2004; Lovelace et al. 2005) and the white dwarfs (Cumming 2002). Studies have shown that under favorable conditions the surface magnetic field of a star can decrease by a factor of 100 with its subsequent reemerging due to diffusion through the layer of accreted plasma.

3.3. Spin evolution of AR Sco: general scheme and conditions

Following this approach we can outline the following scheme of the AR Sco evolution. Prior to the stage of active mass transfer the magnetic field strength on the surface of the white dwarf in AR Sco was close to its current value and the mass exchange rate was $\dot{M} \ll \dot{M}_{\text{su}}$. As the normal component overfilled its Roche lobe, the mass exchange rate increased up to $\dot{M}_{\text{su}} \sim 10^{19} \text{ g s}^{-1}$. This led to decrease of the magnetospheric radius of the white dwarf down to $R_{\text{m}}^{(0)} \leq 10^{10} \times \mu_{34}^{4/7} \dot{M}_{19}^{-2/7} M_{0.8}^{-1/7} \text{ cm}$ (here $\mu_{34} = \mu/10^{34} \text{ G cm}^{-3}$) and start of disk accretion onto its surface provided $R_{\text{m}}^{(0)} < R_{\text{cor}}$. The latter condition could be satisfied if the initial spin period of the white dwarf was $P_0 \geq 10$ min.

Due to the surface field of the white dwarf screening by plasma accumulating on its polar caps the magnetospheric radius of the white dwarf was further decreasing. At the final stages of spin-up epoch the magnetic field strength on the white dwarf surface did not exceed 10 MG, that allowed spin-up of the white dwarf to the current value of its rotation period.

Assuming that the magnetospheric radius of the white dwarf is decreasing at the same rate as its corotation radius, one can estimate the minimum possible spin-up time of the white dwarf with account for screening of its magnetic field in the process of accretion from equation $I\dot{\omega}_s = \dot{M}_{\text{su}} (GM_{\text{wd}} R_{\text{cor}})^{1/2}$ as

$$\Delta t_{\text{min}} = \frac{(2\pi)^{4/3} I}{\dot{M}_{\text{su}} (GM_{\text{wd}})^{2/3} P_s^{4/3}}. \quad (6)$$

After the stage of active mass exchange is finished the magnetic field of the white dwarf is regenerating in the process of diffusion through the layer of degenerate matter. The timescale of this process can be evaluated following Cumming (2002) as

$$\tau_{\text{diff}} \simeq 3 \times 10^8 \text{ yr} \times (\Delta M_{\text{a}} / 0.1 M_{\odot})^{7/5}. \quad (7)$$

For the magnetic field of the white dwarf to reemerge before its spin period can significantly increase we should require $\tau_{\text{diff}} \leq t_{\text{sd}}$. Substituting expression (7) and solving this inequality for ΔM_{a} we find for the parameters of AR Sco:

$$\Delta M_{\text{a}} \leq 0.009 M_{\odot} \times P_{117}^{5/7} \left(\frac{\dot{P}}{3.9 \times 10^{-13} \text{ s s}^{-1}} \right)^{-5/7}. \quad (8)$$

Taking into account that the amount of matter accumulated on the white dwarf surface during the spin-up stage can be estimated as $\Delta M_{\text{a}} \geq \dot{M}_{\text{su}} \Delta t_{\text{min}}$ and substituting (6), we can get upper limit for the moment of inertia of the white dwarf in AR Sco providing its evolution to be described in terms of accretion-driven spin-up:

$$I \leq 2.1 \times 10^{50} \text{ g cm}^2 \times P_{117}^{4/3} M_{0.8}^{2/3}. \quad (9)$$

This condition is satisfied (Andronov & Yavorskij 1990) for any white dwarf of the mass in the range $0.81 - 1.29 M_{\odot}$ determined by Marsh et al. (2016). This indicates that the origin of AR Sco can be explained within the scenario in which the accretion-driven spin-up is accompanied by screening of the magnetic field of the accretor initially proposed for AE Aqr (for further discussion see Ikhsanov & Beskrovnaya 2012).

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References

- Andronov, I.L., Yavorskij, Yu.B. 1990, Contr. Astron. Obs. Skalnate Pleso, 20, 155
 Bisnovatyi-Kogan, G.S., Komberg, B.V. 1974, Sov. Astron., 18, 217
 Cumming, A. 2002, MNRAS, 333, 589
 Frank, J., King, A., Raine, D. 2002, "Accretion Power in Astrophysics", Cambridge Univ. Press
 O.C. de Jager, P.J. Meintjes, D. O'Donoghue, E.L. Robinson 1994, MNRAS, 267, 577
 Ikhsanov, N.R. 1998, A&A, 338, 521
 Ikhsanov, N.R. 1999, A&A, 347, 915
 Ikhsanov, N.R., Biermann, P.L. 2006, A&A, 445, 305
 Ikhsanov, N.R., Beskrovnaya, N.G. 2012, Astron. Rep., 56, 595
 Konar, S., Choudhuri, A.R. 2004, MNRAS, 348, 661
 Livio, M., Pringle, J.E. 1998, ApJ, 505, 339
 Lovelace, R.V.E., Romanova, M.M., Bisnovatyi-Kogan, G.S. 2005, ApJ, 625, 957
 Marsh, T.R., Gänsicke, B.T., Hümmerich, S., et al. 2016, Nature, 537, 374
 Nomoto, K., Saio, H., Kato, M., Hachisu, I. 2007, ApJ 663, 1269
 Schönberner, D., Driebe, T., Blöcker, T. 2000, A&A, 356, 929
 Spitkovsky, A. 2006, ApJ, 648, L51